On the possible wave-packet collapse induced by topological disconnectivity and experimental suggestions

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The purpose of this paper is to explore the possibility of a wave-packet collapse induced by topological disconnectivity, based on the discussions of the wave-corpuscle duality. Several experimental suggestions are proposed to test this sort of wave-packet collapse based on quantum interference.

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I. INTRODUCTION

Driven by the remarkable quantum manipulations such as the ability to control individual atoms and the realization of gaseous Bose-Einstein condensates, the second quantum revolution is under way. We believe that in the second quantum revolution, a lot of important techniques will have practical applications, such as quantum cryptography, and quantum-controlled chemistry, etc. The advances in quantum manipulation also give us a golden opportunity to test further the basic concepts of quantum mechanics, whose meaning has long been debated. A well-known example is the experimental test [1] of Bell's inequality [2]. In the last few years, there have been significant advances for the loophole-free test of Bell's inequality [3, 4, 5, 6]. Recently, an almost ideal realization of Wheeler's delayed-choice experiment was reported with a single-photon pulse [7]. Most recently, a previously untested correlation between two entangled photons was measured in [8], to test an inequality proposed by Leggett based on a non-local realistic theories [9]. These theoretical and experimental advances have deepened our understanding of quantum mechanics. In the near future, we expect that experiments will provide more convincing tests about the unique concepts in quantum mechanics, such as nonlocality, wave-packet collapse, and wave-corpuscle duality, etc [10].

In this work, we consider the possibility of a wave-packet collapse induced by topological disconnectivity, based on the well-known wave-corpuscle duality and a simple gedanken experiment. Several experimental suggestions are proposed to test this wave-packet collapse based on quantum interference. Although an experimental investigation of this wave-packet collapse may be quite challenging, we believe that the rapid advances of quantum manipulation will make this sort of experiment become promising.

The paper is organized as follows. In Section 2, a possible wave-packet collapse induced by topological disconnectivity is discussed based on the wave-corpuscle duality and a gedanken experiment. In Section 3, the strong disconnectivity and weak disconnectivity are discussed. In Sections 4 and 5, several experimental suggestions are proposed to test this wave-packet collapse for the situations of strong disconnectivity and weak disconnectivity, respectively. In the last section, a brief summary and discussion is given.

II. A GEDANKEN EXPERIMENT AND WAVE-PACKET COLLAPSE INDUCED BY TOPOLOGICAL DISCONNECTIVITY

We first consider a gedanken experiment shown in Fig. 1. More realistic experimental proposals will be discussed in Sections 4 and 5. In Fig. 1(a), there are two connected boxes and a shutter. In each box, there is a trapping potential V_1 and V_2, respectively. The purpose of these two trapping potentials is to make the wave packet of a particle be highly spatially localized, so that the direct contact between the particle and the box can be omitted. It is also required that the direct contact between the particle and the shutter can be omitted. In an experiment, this can be prepared and tested by firstly preparing a particle trapped by the potential V_1 in the left box. The wave function of the particle is assumed as Ψ_1. Then, one closes the shutter to see whether the closing of the shutter has an influence on the wave packet of the particle. If the closing of the shutter has negligible influence on the particle, we think that there is no direct contact between the particle and the shutter, although the closing of the shutter has made the left

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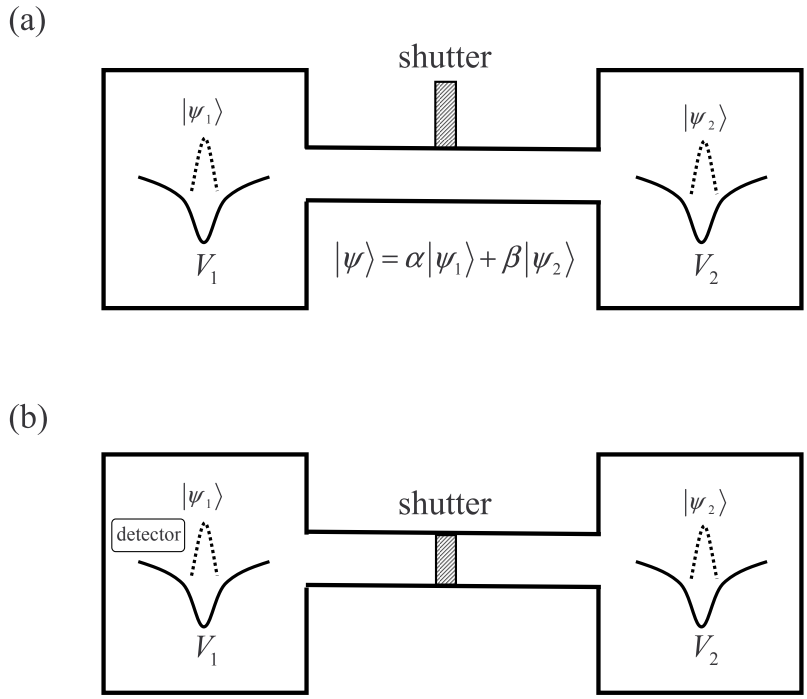

FIG. 1: Schematic of a gedanken experiment. In Fig. 1(a), the initial single-particle quantum state is a coherent superposition state of two spatially-separated wave packets in two connected boxes. In Fig. 1(b), after the closing of the shutter, two boxes become disconnected and closed. We consider in the present work the question whether the closing of the shutter has an essential influence on the quantum state $|\Psi\rangle = \alpha|\Psi_1\rangle + \beta|\Psi_2\rangle$.

and right boxes become disconnected. It is similar for a particle in the right box, whose wave function trapped in the potential V_2 is assumed as Ψ_2.

We consider a single particle whose quantum state is a coherent superposition state, which is given by $|\Psi\rangle = \alpha|\Psi_1\rangle + \beta|\Psi_2\rangle$. Let us discuss the following problem:

After two boxes become disconnected by closing the shutter (in the closing process, there is no external perturbation on the particle and the direct contact between the shutter and the wave packet of the particle can be omitted), is there an essential change in the quantum state of the particle?

For this seemingly simple problem, one is likely to have completely different answers.

Point of view I —— *There is no influence on the single-particle quantum state based on the wave aspect of the particle.*

In our gedanken experiment, it is required that for a particle (whose quantum state is Ψ_1) in the left box, the closing of the shutter has negligible influence on the particle. It is also required that the closing of the shutter has negligible influence on the particle (whose quantum state is Ψ_2) in the right box. Based on the Schrődinger equation, for a particle in the coherent superposition state $\alpha|\Psi_1\rangle + \beta|\Psi_2\rangle$, it seems that the closing of the shutter will also have no influence on the particle. This leads to a predication that there is no influence on the quantum state when one closes the shutter. This predication is similar to the situation of a classical wave. One should note that in these discussions, however, we only address the wave aspect of a particle. In a sense, in these discussions, there is no essential difference between a classical wave and a quantum wave. In the following discussions, we will also consider the role of the particle aspect of the single-particle quantum state.

Point of view II —— *There is an essential influence on the single-particle quantum state based on the consideration of the wave-corpuscle duality.*

The wave-corpuscle duality tells us that the Schrődinger equation describes the wave aspect of the quantum state, while there exists a statistical bond between the wave aspect and corpuscular aspect of a particle. Based on the corpuscular aspect, we try to give here an argument that, there is no single-particle quantum state which could be a coherent superposition of two wave packets existing respectively in two topologically disconnected boxes.

We first assume that there is a quantum state $|\Psi\rangle = \alpha |\Psi_1\rangle + \beta |\Psi_2\rangle$ for two topologically disconnected boxes. In the left box, there is a detector, as shown in Fig. 1(b). After the detector was switched on, if the detector records a particle, what the detector measures is a whole particle because of the corpuscular aspect. This means that the wave packet $\beta |\Psi_2\rangle$ in the right box would disappear, and this wave packet would appear in the left box. It is analogous that, if the detector does not record a particle, the wave packet $\alpha |\Psi_1\rangle$ would disappear in the left box, and appear in the right box. The topological disconnectivity between two boxes means that the wave packet could not disappear in one box and appear in another box, if we assume that there is no extra hidden spatial dimension, or assume that the wave-packet collapse is a process in the ordinary three-dimensional space. These discussions lead to a paradox between the wave-packet collapse (due to the measurement and corpuscular aspect), and the inhibition of the wave-packet collapse due to the topological disconnectivity between two boxes. A solution to this paradox is the suggestion that our initial assumption is invalid, i.e., it is tempting to assume that there does not exist a quantum state which is a coherent superposition of two wave packets trapped respectively in two topologically disconnected boxes.

In the above discussions, we have assumed an inhibition of the nonlocal wave-packet collapse between two topologically disconnected boxes. One should note a subtle meaning of the nonlocality of the wave-packet collapse. Nonlocality has become a key element of quantum mechanics. For a connected region, the wave-packet collapse can happen nonlocally and unblockedly. For two topologically disconnected boxes that a particle in one box can not be transferred to another box without the breaking of two boxes, however, it is quite possible that even nonlocality can not transfer a wave packet from one box to another box. Up to my best knowledge, almost all theoretical and experimental studies on the nonlocality of quantum mechanics are carried out for a fully connected region. In particular, on the experimental side, it seems that the role of disconnectivity on the nonlocality of quantum mechanics has never been studied carefully. At least, the previous experiments do not exclude the possibility of the inhibition of the wave-packet collapse between two topologically disconnected boxes.

If we agree with the point of view that a particle's quantum state only exists in one of the two topologically disconnected boxes, we inevitably get a result that the closing of the shutter would have an essential influence on the quantum state $|\Psi\rangle = \alpha |\Psi_1\rangle + \beta |\Psi_2\rangle$. These analyses suggest the following predication:

$$\begin{aligned} \rho_i &= |\Psi\rangle \langle\Psi| \\ &\Longrightarrow \rho_f = |\alpha|^2 |\Psi_1\rangle \langle\Psi_1| + |\beta|^2 |\Psi_2\rangle \langle\Psi_2| . \end{aligned} \tag{1}$$

Here ρ_i and ρ_f are respectively the density matrix before and after the closing of the shutter.

It is obvious that the probability of finding a particle in the left or right boxes is the same for the density matrices ρ_i and ρ_f. However, there is an essential difference between ρ_i and ρ_f, by noting that in the density matrix ρ_f, there is classical correlation between two boxes, rather than quantum correlation. In the density matrix ρ_f, there is no quantum coherence between $|\Psi_1\rangle$ and $|\Psi_2\rangle$. For a particle described by the density matrix ρ_f, the particle only exists in one of the boxes with probability $|\alpha|^2$ and $|\beta|^2$. If all the confining conditions (the boxes, the shutter and the trapping potential V_1 and V_2) are removed, there would be interference between $|\Psi_1\rangle$ and $|\Psi_2\rangle$ after sufficient expansion time for ρ_i, while there is no interference for ρ_f.

Generally speaking, the measurement of a quantum state consists of two elementary processes: (i) the wave-packet collapse (or decoherence) process; (ii) a transformation of the collapsed quantum state to a classical signal we can apperceive. For the situation discussed in the present work, the closing of the shutter leads to two topologically disconnected boxes. In a sense, the closing of the shutter can be regarded as a measurement by two detectors whose resolution is the region of the left and right box, respectively. Thus, the closing of the shutter leads to the wave-packet collapse of a particle, and complete the first process of a measurement. The second process of the measurement can be completed by switching on the detectors in two boxes, so that the interaction between the particle and the detectors gives classical signal we can apperceive. We want to stress here that even before the detectors in two boxes are switched on, it is possible that there is already a wave-packet collapse by the closing of the shutter. In a sense, the closing of the shutter plays a role of measurement, although further information is needed so that we know which box the particle exists. This is a little like the detection of a particle by a detection screen. When the particle hits the detection screen, the wave-packet collapse is completed. However, we still need to have a look at the detection screen to know the location of the particle. Of course, if the closing of the shutter is regarded as a measurement process, because there is no spatial contact between the shutter and wave packets of the particle, it is different from the ordinary measurement process. In a sense, it is a sort of quantum measurement process induced by topological disconnectivity.

The different results in the *point of view I and point of view II* lies in that in the *point of view I* only the wave aspect of a quantum particle is considered. It is well known that the wave-corpuscle duality is an essential element in quantum mechanical principle, and wave-corpuscle duality is the root of the mystery of quantum mechanics. The Schrődinger equation is in a sense invalid when the corpuscular aspect is considered, such as the nonlocal wave-packet collapse. Therefore, in a sense, the *point of view II* is obtained based on more "standard" quantum mechanics, compared to that of the *point of view I*.

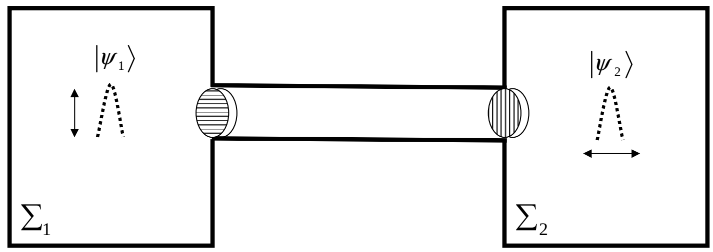

FIG. 2: Schematic is an example of weak disconnectivity.

III. THE DEFINITION OF STRONG DISCONNECTIVITY AND WEAK DISCONNECTIVITY

In the *point of view II* about the wave-packet collapse process given by Eq. (1), it relies on two assumptions: wave-corpuscle duality and wave-packet collapse being a process in the ordinary three-dimensional space. The *point of view II* is a natural result from the assumption that a particle can not exist simultaneously in different disconnected regions. We see that the definition of topologically disconnected regions is necessary to consider further the problem in the present work.

There are two different topological disconnectivities:

(i) For a particle existing in a region Σ_1, under any coherent quantum manipulation, if the wave packet of the particle can not be transformed into another region Σ_2, these two regions Σ_1 and Σ_2 are regarded as *strong disconnectivity*.

(ii) For a particle existing in a region Σ_1, there is a situation that, the manipulation of the spatial wave function alone can not transform the particle into another region Σ_1. Together with a manipulation of the internal state, however, one may transform coherently the wave packet into the region Σ_2. We call this situation as *weak disconnectivity*.

To make the definition of the weak disconnectivity more clearly, we give here an example of weak disconnectivity. In Fig. 2, there are two coherently separated photon wave packets with vertical polarization and horizontal polarization. In the connection region, there are horizontal polarizer and vertical polarizer. The cavities Σ_1 and Σ_2 are disconnected in a sense, because the left (right) photon with vertical (horizontal) polarization can not transform into the right (left) cavity without the changes of the polarization direction. However, if the polarization of the photon is changed with some quantum manipulations in the cavities, the wave packet can transform between two cavities. In this situation, these two cavities are weakly disconnected.

In my opinion, if the closing of a shutter leads to a strong disconnectivity, it is possible that there would be a wave-packet collapse for the coherently superposed quantum state. As for the situation of weak disconnectivity, at least in my opinion, it is uncertain what will happen in an experiment. Frankly speaking, I believe only future experiments could tell us what will happen for both cases. In the following sections, I will try to give several experimental schemes to answer these problems in future experiments.

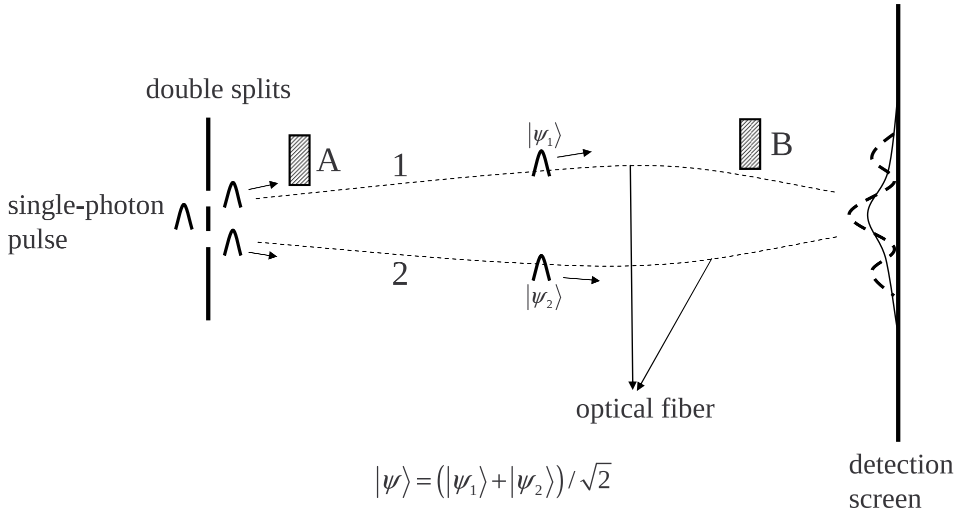

FIG. 3: Schematic of the Young double-slit experiment. If two shutters A and B placed along the optical fiber 1 are always open, there should be clear interference pattern on the detection screen shown by the dashed line. When two shutters are manipulated appropriately, *the point of view I* still predicts the interference pattern shown by the dashed line, while the *point of view II* gives the predication of no interference pattern shown by the solid line.

IV. THE EXPERIMENTAL SUGGESTIONS FOR STRONG DISCONNECTIVITY

In this section, we will give several experimental schemes for the situation of the strong disconnectivity.

A. The experimental suggestion I

We consider a double-slit interference experiment shown in Fig. 3. The Young double-slit experiment has been discussed widely for the complementarity between the corpuscular aspect and wave aspect. The single-photon pulse is spatially separated after a photon passes through the double slit in Fig. 3. After the photon passes through the double slit, the quantum state of the photon is confined in two optical fibers. For this sort of experiment, there is clear interference pattern in the detection screen when two shutters A and B are always open. In a real experiment, the connection between the double slit and the optical fibers may be realized by using a beam splitter to play the role of the double slit. For this double-slit experiment, the density matrix is

$$\rho_1 = |\Psi\rangle \langle\Psi| \,, \tag{2}$$

with $|\Psi\rangle = (|\Psi_1\rangle + |\Psi_2\rangle)/\sqrt{2}$. For a series of single-photon pulses with overall photon number N, the density distribution on the detection screen is then

$$\begin{aligned} n_1 &= \langle \mathbf{r}|\rho_1|\mathbf{r}\rangle \\ &= N\left[\frac{1}{2}\left|\langle \mathbf{r}|\Psi_1\rangle\right|^2 + \frac{1}{2}\left|\langle \mathbf{r}|\Psi_2\rangle\right|^2 + \mathrm{Re}\left(\langle \mathbf{r}|\Psi_1\rangle \langle \Psi_2|\mathbf{r}\rangle\right)\right]. \end{aligned} \tag{3}$$

The last term is the well-known interference term.

As a comparison, we consider another double-slit experiment by considering the role of two mechanical shutters A and B placed along the optical fiber 1. The mechanical shutters are used so that one considers experimentally the situation of the strong disconnectivity. During the propagation of the photon wave packet between two shutters in the optical fiber 1, two shutters close and then open simultaneously. After the two shutters are closed, the existence region of the quantum state $|\Psi_1\rangle$ and the existence region of the quantum state $|\Psi_2\rangle$ become topologically disconnected. If the *point of view II* (the wave-packet collapse given by (1)) is correct, the closing of the shutter makes the density matrix become

$$\rho_2 = \frac{1}{2}\left|\Psi_1\right\rangle\left\langle\Psi_1\right| + \frac{1}{2}\left|\Psi_2\right\rangle\left\langle\Psi_2\right|. \tag{4}$$

Before the possible single-photon pulse arrives at the shutter B, two shutters open simultaneously. For every single-photon pulse, there is a manipulation of the closing and opening of two shutters during the propagation of the photon wave packet between two shutters. In this situation, for a series of photon pulses with overall photon number N, the density distribution on the detection screen is

$$n_2 = \langle\mathbf{r}|\rho_2|\mathbf{r}\rangle = N\left[\frac{1}{2}\left|\langle\mathbf{r}|\Psi_1\rangle\right|^2 + \frac{1}{2}\left|\langle\mathbf{r}|\Psi_2\rangle\right|^2\right]. \tag{5}$$

We see that there is no interference pattern based on the *point of view II.* If the *point of view I* is correct, we expect that there is still clear interference pattern.

B. experimental suggestion II

We now consider another experimental suggestion. In Fig. 4, a single-photon pulse is split into two wave packets by the beam splitter denoted by BS1. Two spatially separated photon pulses propagate in the optical fibers along different paths denoted by x and y. Two mirrors (denoted by M) bring two wave packets together at a beam splitter denoted by BS2. The light path is devised so that these two photon pulses arrive at BS2 simultaneously. The phase shifter controls the relative phase ϕ when two photon pulses arrive at BS2. The role of BS2 is shown by the inset in this figure.

Without the shutters, after very simple derivation, the density matrix is

$$\rho_a = \left|\Psi\right\rangle\left\langle\Psi\right| \tag{6}$$

with $|\Psi\rangle = \frac{1}{2}\left(e^{i\varphi}-1\right)|x\rangle + \frac{1}{2}\left(e^{i\varphi}+1\right)|y\rangle$. For a series of photon pulses with overall photon number N, the average photon number recorded by the detectors D_x and D_y is respectively given by

$$N_x = N\left\langle x|\rho_a|x\right\rangle = \frac{N}{4}\left|e^{i\varphi}-1\right|^2, \tag{7}$$

and

$$N_y = N\left\langle y|\rho_a|y\right\rangle = \frac{N}{4}\left|e^{i\varphi}+1\right|^2. \tag{8}$$

Because of the interference between the photon's two wave packets, N_x and N_y display oscillating behavior with the relative phase φ.

Similar to the preceding experimental suggestion, during the propagation of the pulsed photon between two shutters, two mechanical shutters shown in Fig. 4 close and then open simultaneously. Based on the *point of view II*, the density matrix is

$$\rho_b = \frac{1}{2}\left|\Psi_x\right\rangle\left\langle\Psi_x\right| + \frac{1}{2}\left|\Psi_y\right\rangle\left\langle\Psi_y\right| \tag{9}$$

with

$$\left|\Psi_x\right\rangle = \frac{e^{i\varphi}}{\sqrt{2}}\left(|x\rangle + |y\rangle\right), \tag{10}$$

and

$$\left|\Psi_y\right\rangle = \frac{1}{\sqrt{2}}\left(-|x\rangle + |y\rangle\right). \tag{11}$$

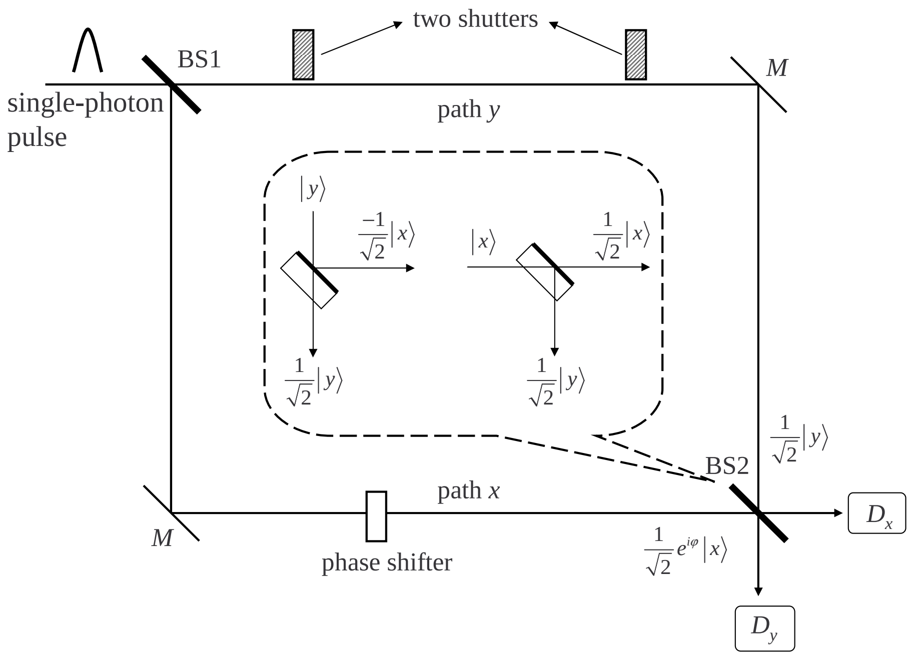

FIG. 4: Schematic of an experimental suggestion for the situation of the strong disconnectivity.

In this situation, we have

$$N_x = N \langle x|\rho_b|x\rangle = \frac{N}{2}, \tag{12}$$

and

$$N_y = N \langle y|\rho_b|y\rangle = \frac{N}{2}. \tag{13}$$

Because the photon pulses propagating along the paths x and y become incoherent due to the manipulation of two shutters, N_x and N_y do not depend on the relative phase φ.

We see that there is obvious difference based on the *point of view I* and *point of view II*. In particular, for $\varphi = 0$, the *point of view I* predicts that $N_x = 0$, while the *point of view II* predicts that $N_x = N/2$.

V. THE EXPERIMENTAL SUGGESTION FOR WEAK DISCONNECTIVITY

Now we turn to consider an experimental suggestion about the situation of the weak disconnectivity. The experimental suggestions in the preceding section have a shortcoming that the response time of the mechanical shutter should be very short. If one uses a single-photon pulse, the response time of the mechanical shutter should be smaller than L/c, with L and c denoting the length of the optical fiber and the velocity of light. This is quite challenging for a mechanical shutter. For the situation of the weak disconnectivity, however, the application of the Pockels cell would overcome the problem of the response time.

Compared with Fig. 4, the path y in Fig. 5 has special design with two vertical polarizers and two Pockels cells (PC1 and PC2). The response time of the Pockels cell can be of the order of ns. The photon from the single-photon source has vertical polarization. The wave packet of the nth single photon propagating along the path y arrives in succession the left polarizer, PC1, PC2, and the right polarizer with times t_{n0}, t_{n1}, t_{n2}, and t_{n3}. We have $t_{n1} - t_{n0} = L_1/c$, $t_{n2} - t_{n1} = L_2/c$ and $t_{n3} - t_{n2} = L_3/c$. The Pockels cell has the role that once a voltage is applied on it, the polarization of the incident light will be rotated by $90°$. The time sequence of the voltage for two Pockels

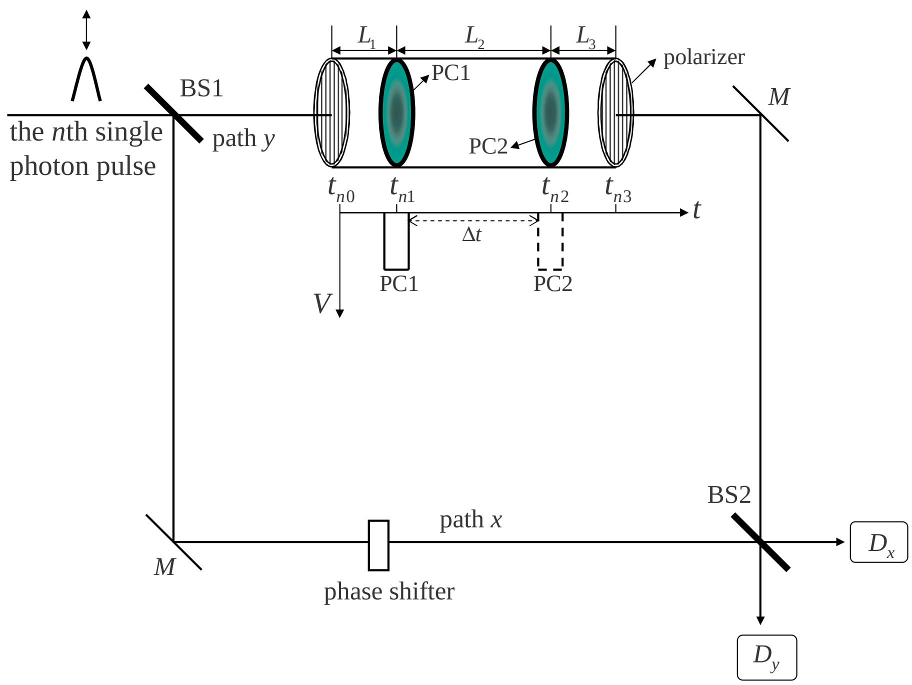

FIG. 5: Schematic of an experimental suggestion for the situation of the weak disconnectivity.

cells is shown respectively by solid and dashed lines in Fig. 5. After the time t_{n1}, the polarization of the wave packet of the photon propagating along path y becomes horizontal. In this situation, we see that between the time interval Δt (shown by the dashed line), the interior and exterior regions of the box show a sort of weak disconnectivity. The merit of this experimental scheme lies in that because of the rapid response of the Pockels cell, it is more feasible than that of the strong disconnectivity shown in Fig. 4. By checking whether there is interference phenomena recorded by the detectors D_x and D_y, we will know whether there is a wave-packet collapse because of the weak disconnectivity.

VI. SUMMARY AND DISCUSSION

In summary, we have explored a possible wave-packet collapse induced by topological disconnectivity. At least for the situation of the strong disconnectivity, I think that there is a possibility of this sort of wave-packet collapse, based on the consideration of the wave-corpuscle duality. Several experimental suggestions are proposed to test this wave-packet collapse induced by topological disconnectivity.

One of the main purpose of this paper is to show that there is interesting physics in future experiments to test the wave-packet collapse induced by topological disconnectivity. If the *point of view I* is verified (in particular for the situation of the strong disconnectivity), the concept of nonlocality of quantum mechanics can be extended to disconnected regions. This means that the wave-packet collapse can be regarded as not only nonlocal, but also in a sense a process beyond the ordinary three-dimensional physical space. Before the final verification of the *point of view I*, I could not speak too much about the meaning of the wave-packet collapse beyond the ordinary three-dimensional space. If the *point of view II* is verified, it would establish a new type of wave-packet collapse. Note that this sort of wave-packet collapse is quite different from the environment-induced decoherence [11, 12, 13]. In the environment-induced decoherence, there is a contact between the wave packet and the environment (or thermal source). For example, in a beautiful decoherence experiment by using atom interferometry [14], the spontaneously emitted photons play a role of contact between the spatially separated atomic wave packets and environment.

Our discussion in this work is different from the delayed-choice experiments [15] suggested by Wheeler [16, 17]. The delayed-choice experiment studied the interesting quantum interference effect, if the decision for the observation of a photon in one of the paths is made after the photon has passed through a beam splitter. In this sort of experiment,

there is also no contact between the wave packet and the apparatus (a Pockels cell and a Glan polarizing prism in [15]). In our gedanken experiment, however, two shutters will produce two topologically disconnected regions. In fact, after careful searching the relevant experiments, we find that almost all the quantum interference experiments do not address the situation of controllable connected and disconnected regions. The whole region is always connected in previous Young double-slit experiments, atom interferometer, etc.

Considering the great challenge of controllable disconnected regions in an experiment, I think that it is almost impossible to distinguish the *point of view I* and *point of view II* by an accidental experiment. I believe that all previous experiments do not give us clear evidence to verify which point of view is more reasonable. Careful division of an experiment is needed to tell us which point of view is correct. The challenge of this sort of experiment can be given by a simple analysis. For the scheme shown in Fig. 3 and Fig. 4, if the response time of two electromechanical shutters is a microsecond, the length of the optical fiber should be larger than 300 m. This means that there is severe request on the quality of the optical fiber and experimental environment, so that the random phase during the propagation of the photon pulse in the optical fiber is suppressed largely. One method to overcome this problem is the development of submicrosecond electromechanical shutters. Another method is the application of atom interferometer [18] to investigate our problem. For this sort of experiment, two shutters and a cavity should be placed in the vacuum chamber. After the splitting of an atom, one of the wave packets passes through the cavity, and the closing of two shutters can make the cavity become completely closed. For the shutters with response time of a microsecond and the atoms with velocity of 10 m/s, the length of the cavity should be larger than 10^{-5} m. Therefore, it is possible that our problem could be answered with the development of atom interferometers.

Acknowledgments

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